

5/PRTS

10/529018

Description JC17 Rec'd PCT/PTO 24 MAR 2005

Inductive flow meter for electrically conductive  
liquids

5

The invention relates to inductive flow meters having the features of the preamble of patent claim 1.

Flow meters of the type considered here are used to determine the flow of electrically conducting liquids through channels or tubes of circular cross section, in particular. In a channel section having an electrically insulating channel wall or tube wall, there are provided at mutually opposite points of a channel cross section punctiform electrodes that are electrically coupled to the electrically conducting liquid, are exposed to the channel interior, in particular, and are connected to the conducting liquid in a conducting fashion. Running perpendicular to the connecting line between the electrodes, and perpendicular to the flow lines of the conducting liquid flowing through the channel or the tube are the field lines of a magnetic field that is generated by a permanent magnet arrangement or, in particular by a coil arrangement. Conductor paths which run from one punctiform electrode to the other punctiform electrode and which penetrate the entire tube cross section or channel cross section of the tube section or channel section containing the electrodes can, when the conducting liquid is moving along the channel or tube, be understood as conductors which are moving in the magnetic field and in which liquid flow induces voltages that are tapped by the punctiform electrodes via connections led through the insulating channel wall or tube wall, and are a measure of the flow of the conducting liquid through the tube or the channel.

Upon closer scrutiny, the output signal of an inductive flow meter of the type described above that can be

tapped by the electrodes may be specified as follows:

$$S \sim \int_{(Vol)} (\vec{B} \times \vec{W}) \cdot \vec{v} d(Vol).$$

- 5 The integral over the volume is formed by the respective product value of vectors of three vector fields, of which  $\vec{B}$  is the magnetic induction in the cylindrical space surrounding the flow channel having the channel inner cross section and having a specific  
10 length upstream and downstream of the radial plane containing the electrodes, and  $\vec{W}$  denotes a weight vector field that is to be understood as a field of vectors in the previously defined cylindrical space and which characterizes the configuration of the conductor  
15 paths between the electrodes in the cylindrical space. Finally,  $\vec{v}$  denotes the vector field in said cylindrical space with vectors corresponding to the speeds of the particles of the conductive liquid.
- 20 If the values of  $\vec{B}$  were constant in modulus and direction (homogeneous magnetic field), and if the values of the weight vector field  $\vec{W}$  were corresponding flow paths, constant in modulus and direction, running parallel to one another between parallel electrodes,  
25 the partial product  $\vec{B} \times \vec{W}$  would be constant in such a way that non-uniform and/or asymmetric velocity distributions of the flow, which is to be investigated, of the electrically conductive liquid through the flow channel section do not lead to measured value  
30 falsifications.

It is true that with little effort the magnetic field of the magnetic field generation system can be formed such that it is substantially homogeneous in the region  
35 of the interior of the flow channel section, whereas the weight vector field is in no way homogeneous given a flow channel section of round cross section and given essentially punctiform electrodes situated

diametrically opposite one another. This is shown directly by the following consideration:

If these essentially entirely overlapping conductor paths are drawn in tube cross sections or channel cross sections, it will be seen that a conductor path concentration is present in the region near the punctiform electrodes in such a way that movements of the conductor paths because of the flow of the conducting liquid in these regions exert a particularly strong influence on the signal that can be tapped from the electrodes.

If they are laminar, characteristic flows in the flow channel section of an inductive flow meter can have a velocity profile that is rotationally symmetrical with reference to the flow channel middle axis in the undisturbed state, or can, given an asymmetric disturbance, exhibit a flow profile whose maximum is offset laterally in the radial direction from the flow channel middle axis. For high flow velocities, the flow can become turbulent in such a way that the flow profile exhibits a plateau area with reference to the flow channel cross section, and areas of lower flow velocity near the edge.

Both deformations of the flow profile as a function of the flow velocity, and asymmetries in the flow profile influence a measurement result obtained with an inductive flow meter of the type considered here in a way that falsifies measured values.

An attempt has already been made in the technical teaching of German patent specification 1 295 223 to inhomogeneously form the magnetic field in a flow channel section of an inductive flow meter in such a way as thereby to counteract the influence of the necessarily present inhomogeneity of the weight vector field on the measurement result given a non-uniform

- flow distribution over the flow channel cross section. German patent specification 1 295 223 proposes for this purpose that the magnet arrangement, that is to say the magnetic field generation system, be formed such that
- 5 the field component in the radial plane containing the electrodes, and in planes parallel thereto decreases from the inside to the outside in the direction of the connecting line between the electrodes.
- 10 In order to reduce the falsification of measured values owing to non-uniform flow distribution, an attempt has already been made to compensate for the increased influence of the region of the flow cross section near the electrodes on the magnitude of the measurement
- 15 signal by virtue of the fact that, for example in accordance with the German laid-open patent application 26 22 943, provision was made when generating the magnetic field by means of energized coils of additional compensation coils that generated in the
- 20 cross-sectional plane of the flow channel section containing the electrodes, or else upstream or downstream thereof, magnetic fields that permeated the flow for generating the induced voltages in the conductor paths in those regions that are to be
- 25 assigned to the regions located in the immediate vicinity of the electrodes, the orientation of these magnetic fields being directed opposite to the main magnetic field.
- 30 The structure of the overall device resulting from this is comparatively complicated, the parts of the magnet system located in the vicinity of the electrodes and which act directly on the region of very high conducting path density requiring very exact mounting
- 35 and extremely fine focusing.

An inductive flow meter that acts in a similar manner to the device previously considered and has a simplified structure of the magnetic field generation

system is described in the German laid-open patent application 400 20 30.

Finally, European patent application, publication number 41 80 33, discloses an inductive flow meter of the type considered here having a main magnetic field generation system which is offset by 90° with reference to the pair of measuring electrodes situated opposite one another and is equipped in each case with pole 5 shoes bearing against the outer surface of the flow channel wall over a restricted angular range of said wall and with auxiliary coils that wrap around these pole shoes and bear closely against the outer surface of the flow channel section over a relatively large 10 angular range in such a way that an approximately sinusoidal magnetic flux distribution of the magnetic field generation system is achieved over a lateral surface, spanning less than 180° in a circumferential direction, of the flow channel wall between the 15 measuring electrodes.

It emerges that with this known inductive flow meter, as well, it is not possible to achieve entirely satisfactory insensitivity of the measurement result to 25 variations, dependent on flow velocity, in the flow profile, and to asymmetric distortions of the flow profile of the flow in the flow channel section.

It is therefore the object of the present invention to 30 configure an inductive flow meter of the general type considered here so as to achieve in conjunction with a comparatively simple design and simple production of the magnetic field generation system a substantially improved insensitivity to measured value falsifications 35 owing to variations, dependent on flow velocity, of the flow profile in the flow channel cross section, or owing to asymmetries in the flow profile relative to the flow channel middle axis.

This object is achieved according to the invention by means of an inductive flow meter having the features in accordance with claim 1. It may be stressed here that an insensitivity to measured value falsifications that  
5 is improved by up to an order of magnitude is achieved according to the invention, the designer being offered a surprisingly simple concept for achieving the object for manifold applications.

10 Advantageous refinements and developments are the subject matter of the patent claims dependent on claim 1, the content of which is hereby expressly rendered a constituent of the description without repeating the wording at this juncture.

15 Some exemplary embodiments are explained below in more detail with the aid of the drawings, a schematic mode of representation that chiefly illustrates the mode of operation being selected in the drawings, and no value  
20 being placed on being true to scale. In the drawings:

25 figure 1 shows a partly sectional perspective illustration of an inductive flow meter of the general type considered here for the purpose of explaining terms and geometric relationships;

30 figure 2 a perspective view of a part of an inductive flow meter for the purpose of explaining how an asymmetric distortion of the velocity vector field in the flow channel cross section relative to the flow channel middle axis influences measured value falsifications;

35 figure 3 shows a perspective view of a part of an inductive flow meter for the purpose of explaining how a change in the flow velocity vector field, which is

5

symmetrical in relation to the flow channel middle axis, upon transition from a laminar flow to a turbulent flow influences measured value falsifications;

10

figure 4 shows a perspective view of a part of an inductive flow meter through whose flow channel cross section a laminar flow of the electrically conducting liquid passes;

15

figure 5 shows a schematic perspective view of an inductive flow meter of the type specified here, having a magnetic field generation system formed from field coils;

20

figure 6 shows a schematic perspective view of an inductive flow meter of the type specified here, having a magnetic field generation system formed from a magnetic closed circuit with pole shoes; and

25

figures 7A to 7F show developments of the flow channel inner wall in a circumferential region between the midpoint between the measuring electrodes up to a measuring electrode, for various embodiments of an inductive flow meter of the type specified here.

35

The inductive flow meter of the general type considered here consists in its basic constituents as illustrated in figure 1 of a flow channel section 1 in the shape of a tube made from an electrically insulating material. The central longitudinal axis of the flow channel section 1 is denoted by Z. Located in the middle of the

longitudinal extent of the flow channel section 1 at locations which are situated diametrically opposite one another over the relevant flow channel cross section are measuring electrodes 2 and 3, which, are, for  
5 example, approximately punctiform and are connected to a voltmeter 6 via measuring lines 4 and 5, respectively, that reach through the wall of the electrically insulating flow channel section 1. On the inside of the flow channel section 1, the measuring  
10 electrodes 2 and 3 can make direct contact with the electrically conducting liquid flowing through the flow channel section 1, or else can be coupled capacitively to the electrically conducting liquid where a magnetic field generation system of the inductive flow meter is  
15 used in a way known to the person skilled in the art to excite alternating current such that, in this case, the measuring electrodes need not lie exposed on the inside of the flow channel section 1. The distance of the cross-sectional plane of the flow channel section 1  
20 containing the measuring electrodes 2 and 3 from the end of said section lying upstream, and from the end thereof lying downstream may be denoted respectively by z.  
  
25 Finally, a magnetic field generation system 7 is indicated by block symbols in figure 1. This system generates an induction vector field  $\vec{B}$  represented by vectors of the magnetic induction, the magnetic field lines permeating the wall of the flow channel section 1  
30 and its interior and being oriented substantially perpendicular to the central axis Z and perpendicular to the diametrical line, connecting the measuring electrodes 2 and 3, of the flow channel section.  
  
35 The length of  $2z$  considered here for the interior of the flow channel section 1 is selected here to be approximately equal to the diameter of the flow channel cross section. A magnetic field is generated by the magnetic field generation system 7 may firstly be

- assumed for the purposes of explanation in conjunction with figure 1 to be homogeneous throughout the interior of the flow channel section 1. If an electrically conducting liquid is now guided through the interior of  
5 the flow channel section 1, the flow particles of the liquid have velocities corresponding to the individual velocity vectors of a vector field  $\vec{v}$  that are parallel to the central longitudinal axis Z.
- 10 A multiplicity of conductor paths that permeate the entire interior of the flow channel section 1 both over the channel cross section and over the length of the flow channel section 1 are indicated by dashed lines w in figure 1. If the electrically conducting liquid  
15 moves in accordance with the velocity vector field  $\vec{v}$  through the flow channel section 1, the conductor paths are then to be understood in accordance with the lines w as conductors moved in the magnetic field and in which electromotive forces are respectively induced  
20 because of the movement of the conductor paths in such a way that a resulting induced measuring voltage is finally present between the measuring electrodes 2 and 3 and is measured by the measuring instrument 6 and bears a relationship to the flow rate per time unit of  
25 the electrically conducting liquid.

Because of the orientation and the course of the conductor paths, adopted in the electrically conducting liquid, in accordance with the lines w, the  
30 electromotive forces induced in the individual conductor paths contribute to a different extent to the measuring signal S that can finally be read off at the measuring instrument 6. This results because, at least in specific sections of their course between the  
35 measuring electrodes 2 and 3, the conductor paths have an orientation differing from the course perpendicular to the central longitudinal axis Z and perpendicular to the field lines of the magnetic field, and also exhibit different lengths in each case.

It is justifiable for this reason to consider the conductor path configuration as a conductor path configuration weight vector field  $\bar{W}$ , this vector system, denoted below for short as weight vector field,  
5 taking account of the orientation components of the conductor path course that are responsible for the induction of electromotive forces.

The signal S that can be read out at the voltmeter 6  
10 may be expressed as follows:

$$S \sim \int_{(Vol)} (\bar{B} \times \bar{W}) \cdot \bar{v} d(Vol)$$

If all the vectors of the flow velocity vector field  $\bar{v}$   
15 that are parallel to the central longitudinal axis 2 are of the same length, that is to say if the flow velocity is constant over the flow channel cross section, there is a linear dependence of the measuring signal S on the flow velocity, since the product  $(\bar{B} \times \bar{W})$   
20 is essentially as an apparatus constant determined by the geometric arrangement in the flow meter.

However, for specific cases of operation of the inductive flow meter the velocity vector field  $\bar{v}$   
25 suffers specific distortions in practice that will be treated briefly in a purely qualitative fashion with reference to figures 2 to 4.

Figure 2 shows a vector field  $\bar{v}$  of the velocity distribution over the flow channel cross section, in which no rotational symmetry of the flow profile is present with reference to the central longitudinal axis Z of the flow channel cross section 1. The region of maximum velocity vectors of the vector field  $\bar{v}$  is  
30 offset asymmetrically downward with reference to the central longitudinal axis Z. This velocity distribution can result, for example, from the fact that there are located in the channel sections upstream of the flow  
35

channel cross section 1 flow obstacles, for example valve spools, tube bends and the like, the effect of which is that the maximal flow vectors of the flow distribution are located, for example, in the lower 5 quadrant of the tube cross section. However, the region of the maximum can also lie in other quadrants, for example in a cross-sectional quadrant adjoined by the measuring electrode 2 or in a cross-sectional quadrant adjacent to the zenith of the flow channel cross 10 section 1, or else in the cross-sectional quadrant adjacent to the measuring electrode 3.

Figure 3 shows a situation in which a transition has taken place from laminar flow (see figure 4) to a 15 turbulent flow because of high flow velocities in the flow channel section 1. The flow profile is approximated in an axial section by a trapezoidal shape, edge sections of low flow velocity having a relatively low radial thickness. In the region of a 20 laminar flow in accordance with figure 4, the flow profile of the vector field  $\bar{v}$  has the shape of a paraboloid of revolution that is symmetrical in relation to the central longitudinal axis Z.

25 Both the position and the size of the asymmetry of the flow profile relative to the central longitudinal axis Z according to figure 2, and the basic shape of a flow profile, symmetrical relative to the central longitudinal axis Z, according to figures 3 and 4, and, 30 finally, also a flow profile in the shape of a paraboloid of revolution in the laminar flow region influence the measuring signal that can be read off at the measuring instrument 6 according to figure 1 in the sense of a measured value falsification, assuming a 35 homogeneous magnetic field B, since deviations in the practical velocity vector fields  $\bar{v}$  from a uniform distribution over the flow channel cross section respectively signify different movements of the conductor paths, illustrated by the linear field w in

figure 1, of the weight vector field  $\bar{W}$ , and thus different contributions to the signal S.

It has now been found that the compensation of the influence, acting to falsify the measured value, of the distortion of the flow velocity distribution over the flow channel cross section by a particular shaping of active area arrangements is very successful, these active area arrangements being those areal formations, 5 on which the field lines of the magnetic field generation system respectively penetrate the flow channel inner wall in a restricted fashion. These active area arrangements lie on the flow channel inner wall between the measuring electrodes, and extend 10 circumferentially in accordance with the angle of wrap of pole shoes or field coil arrangements with reference to the flow channel circumference, as well as in an axial direction corresponding to the axial extent of pole shoes or of field coil arrangements, doing so 15 symmetrically upstream and downstream of the flow channel section radial cross section containing the measuring electrode points.

The following may be stated in this regard with the aid 25 of figures 5 and 6:

Figure 5 shows an embodiment in which the magnetic field generation system assigned to the flow channel section 1 and the measuring electrodes 2 and 3 in the 30 way illustrated is formed by two field coils 7L that closely fit the outer circumferential surface of the flow channel section 1 in the way illustrated, are respectively situated in regions diametrically opposite one another and between the measuring electrodes 2 and 35 3, and which span an angle of wrap denoted in figure 5 by  $2\phi_0$ . The axial extent of the field coils 7L will in each case amount to b in a position that is symmetrical in relation to the radial plane containing the measuring electrodes 2 and 3.

Figure 6 shows in a wholly corresponding way a highly schematic perspective view of an inductive flow meter with a closed circuit 20 forming the magnetic field 5 generation system, which supports a field coil (not illustrated), and which has pole shoes 7P that are located opposite one another across the flow channel section 1 and, with reference to the axial extent, are in turn situated symmetrically relative to the radial 10 plane containing the measuring electrode points and have an axial extent b, while in the circumferential direction they surround the flow channel section 1 of round cross section with an angle of wrap of  $2\phi_0$  in each case, as is made plain by dashed and dotted lines 15 in figure 6.

If a field current is applied to the field coils 7L of the embodiment according to figure 5, or if the field coil of the magnetic closed circuit 20 of the 20 embodiment according to figure 6 are/is excited, then magnetic field lines of the magnetic fields generated by the field coils or the pole shoes 7 in the interior of the flow channel section 1 permeate the bounding inner wall of the flow channel section 1 in a fashion 25 respectively most largely restricted to cylindrical active area arrangements situated diametrically opposite one another and whose cylindrical shape is essentially in accordance with the teaching given here in order in a surprisingly simple way to compensate for 30 influences, which falsify measured values, of distortions in the flow velocity distribution over the flow channel cross section.

The possible shapes of the active area arrangements can 35 be seen from developments of the cylindrical inner wall of the flow channel section 1 in the circumferential region between the cylinder surface line situated centrally between the measuring electrodes 2 and 3, and the cylinder surface line passing through one each of

the measuring electrodes, for example through the measuring electrode 3 in accordance with the illustrations of figures 7A to 7F. In figures 7A to 7F, a dashed and dotted horizontal line R denotes the track  
5 of the intersection between the flow channel inner wall and a radial plane containing the measuring electrodes 2 and 3. All the developed views shown extend over a circumferential angular range of  $\phi=90^\circ$ , and thus respectively constitute a quarter of the inner  
10 circumferential surface of the flow channel section 1.

In the case of the embodiment in accordance with figure 7A, the active area arrangement is denoted by Fa and corresponds qualitatively to that magnetic field  
15 line penetration surface that is generated by the field coil arrangement 7L according to figure 5 in a square of the flow channel inner surface.

If bounding straight lines T1 and T2 are drawn in a  
20 fashion tangential to the active area arrangement Fa and touch the active area arrangement Fa at two points from outside, the shape of the active area arrangement ensures that these bounding straight lines T1 and T2 converge in pairs in the direction of the respective  
25 location of the measuring electrode, that is to say the measuring electrode 3 in the illustrated selected, this condition not being, however, sufficient on its own for the targeted purpose. It is of essential importance that the active area arrangements are shaped such that  
30 there are located between the respective two points of contact concave regions K in which the boundary lines of the active area arrangements Fa have no points of contact of any sort with the tangential bounding straight lines T1 and T2, respectively.

35

In the case of the embodiment according to figure 7B, the active area arrangements Fb are provided by means of constrictions on the basis of corresponding shaping of the field coils 7L in the regions of greater angle

of wrap, such that the concave regions K are enlarged. The active area arrangements F<sub>b</sub> are, however, still respectively inherently closed.

5 In accordance with the embodiment shown in figure 7C, the active area arrangements can also be formed by mutually separate areal formations F<sub>c</sub>, which means that there is provided in a specific range of angle of wrap of small extent a main field coil at which, in each  
10 case in relatively large ranges of angle of wrap directed toward the measuring electrodes 2 and 3, small auxiliary field coils with the same winding senses as that of the main field coil are located. The concave regions K between the boundary lines of the active area  
15 arrangement F<sub>c</sub> and the tangential bounding straight lines T<sub>1</sub> and T<sub>2</sub> can be enlarged further by such a formation if this is desirable in specific cases.

It has emerged that the circumferential extent of the  
20 active area arrangements F<sub>a</sub> and F<sub>b</sub> and F<sub>c</sub> in accordance with the angle of wrap  $2\phi_0$  of the associated field coil arrangement 7L is in the region of at least  $120^\circ$ , preferably more than  $140^\circ$ , ranges of more than  $140^\circ$  for the angle of wrap leading to surprisingly good results.  
25

If the embodiments according to figures 7A to 7C are considered, it is seen that the active area arrangements F<sub>a</sub> and F<sub>b</sub> and F<sub>c</sub> have their area centroid lying closer to the circumferential center of the flow  
30 channel inner surface between the measuring electrodes, while those parts of the active area arrangements that extend further out to the measuring electrodes 2 and 3, respectively, have a lower areal weight. It is to be stated in this regard that very advantageous results  
35 are achieved in the sense of the achievement of the object set when each active area arrangement has in a circumferential region from the circumferential center, situated symmetrically between the measuring electrodes, in accordance with  $\phi=0$  up to  $\phi=\pm\phi_0/2$  at

least 65%, preferably more than 75% of its areal content, and respectively correspondingly has at most 35%, preferably less than 25% of its areal content in the circumferential region from  $\phi = \pm\phi_0/2$  to  $\phi = \pm\phi_0$ .

5

Shown in figure 7D, in a way similar to figure 7A, in a quadrant of the active area arrangements in the developed view as they are defined by field coil arrangements 7L in accordance with figure 5, is the 10 developed view of a quadrant of an active area arrangement Fd such as is defined, for example, by the pole shoe arrangement 7P of the magnetic closed circuit 20 of figure 6. Here, as well, tangential bounding straight lines T1 and T2 which are laid at the active 15 area arrangement Fd and respectively touch the active area arrangement Fd at two points from outside converge in pairs in the direction of the respective location of the measuring electrodes, that is to say in the present case to the location of the measuring electrode 3. 20 Lying between the respective two points of contact here, as well, are concave regions K in which the circumferential lines of the active area arrangements have no points of contact of any sort with the tangential bounding straight lines T1 and T2.

25

Figure 7E shows an active area arrangement Fe in which mutually separate active area elements cooperate. It is evident to the person skilled in the art that such an active area arrangement can be defined by pole shoes 30 that, in departure from the arrangement in accordance with figure 6, has, instead of the integrally attached relatively narrow pole shoe webs, separate auxiliary pole shoes that respectively bear on both sides of main pole shoes, in a fashion situated between the latter 35 and the measuring electrodes, against the respective circumferential surfaces of the flow channel section 1, and are identically permeated with reference to the main pole shoes. By comparison with the embodiment according to figure 7D, the concave regions K have a

larger extent in the case of the design of the active area arrangement Fe.

Finally, the illustration of figure 7F shows the 5 possibility, in the case of active areas not inherently closed, for example in the manner of figures 7C or 7E to arrange between the active area parts symmetrically in relation to both sides of a principle active area element partial surface elements Fu through which field 10 lines of magnetic fields pass that are oriented oppositely to the field lines penetrating the active area arrangements, and which are generated by additional magnetic field generation systems that include additional magnetic closed circuits or 15 additional field coil arrangements. A further improvement in the compensation can be achieved here for specific characteristic distortions of the flow velocity field in the flow channel cross section. However, it is essential that the active area 20 arrangement element lying next to the respective measuring electrode be permeated by field lines that correspond in orientation to those of the main active area arrangement element.